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ELASTIC VELOCITY AND Q FACTOR MEASUREMENTS ON APOLLO 12, 14, AND 15 ROCKS

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Abstract

The Rayleigh wave velocities were measured in one Apollo 12, one Apollo 15, and two Apollo 14 rocks by the impulse technique. For 14310 $v_R = 1.20$ km/sec; for 14321 $v_R \approx 0.9$ km/sec; for 12063, on which the orientation dependence was studied, $v_R = 1.16 - 1.26$ km/sec; for 15555 $v_R = 0.32$ km/sec; and for synthetic rock 10017 analogue $v_R = 2.26$ km/sec. This represents a larger spread by a factor of three than previously reported on lunar igneous rocks. Absolute Q factor measurement were performed on one Apollo 14 rock by the vibrating bar technique. For 14310 $Q \approx 70$ at STP, $Q \approx 10$ in water vapor, $Q \approx 150$ at 5×10^{-8} mm of Hg and $T = 25°C$, and $Q \approx 800$ at 5×10^{-8} mm of Hg and $T \approx -180°C$. Thus the Q-factor is shown to increase under exposure to high vacuum and low temperatures towards values approaching the low end of the range of seismic values ($Q \approx 1000$).

I. Introduction

In this paper, velocity and Q factor measurements are presented which were made on Apollo 12, 14 and 15 returned lunar rocks 12063.96, 14321.211, 14310.86, and 15555.90.

Earlier elastic property measurements on returned lunar samples showed anomalous values with respect to corresponding values known for terrestrial rocks. Unexpectedly low velocities were observed for Apollo 11 rocks (Schreiber et al., 1970; Kanamori et al., 1970) and for Apollo 12 rocks (Kanamori et al., 1971; Wang et al., 1971; Tittmann and Housley, 1971; and Warren et al., 1971). This same trend is again observed in our recent measurements on Apollo 14 samples, and an unusually low velocity has now been observed on Apollo 15 igneous sample rock 15555. The present investigation includes comparisons with terrestrial rocks and synthetic analogues of lunar rocks, studies of microfractures by the scanning electron microscope, correlations between microfracture orientation and Rayleigh wave anisotropy, and elastic measurements under conditions varying from rock saturation with a liquid to high vacuum.

Q values deduced from lunar seismic data are known to be anomalously high ($Q \approx 1000$-3000) in comparison with the Q factors measured for the lunar return samples. Low Q factors were observed for Apollo 11 rocks (Kanamori et al., 1970) and for Apollo 12 rocks (Warren et al., 1971; and Wang et al., 1971). Similarly low Q factors were observed in our measurement on an Apollo 14 sample at standard temperature and pressure (STP). However, we show here that the Q factor can be made to rise strongly under exposure to high vacuum and low temperatures towards values approaching the low end of the range of seismic values.

II. Velocity Measurements

A. Summary of Experimental Results:

Rayleigh wave group velocity measurements were performed on portions of lunar rocks 12063, 14310, and 15555 as well as on a synthetic analogue of lunar rock 10017. The results are presented in Table I together with some additional data from the literature.

Table I

Sample	Rayleigh Wave Velocity (km/sec)	Comments
12038	0.97 - 1.45	Granular basalt (Tittmann and Housley, 1971)
12063	0.94 - 1.26	Diabase
14310	1.20	Basalt
14321	0.90 ± 0.15	Matrix material of breccia
15555	0.28 - 0.34	Olivine basalt, highly fractured
10046	~ 0.7 (calc.)	Micro breccia (Anderson *et al.*, 1970)
Synthetic Analogue of 10017	2.21 - 2.26	Basalt, analogue of lunar rock 10017
Terrestrial Basalt	2.97 - 3.15	Augite basalt with strong flow structure

Most of the measurements were performed by the impulse technique (Tittmann, 1971) which uses ceramic piezoelectric transducers as transmitter and receiver, both placed on one flat surface of a rock. The transducers are separated from the rock by thin soft aluminum foils which serve as acoustic bonds coupling the acoustic energy between transducer and rock. A 0.1 μsec wide voltage pulse applied to the transmitter produces an acoustic impulse which travels radially outward on the surface with the Rayleigh wave group velocity and is detected some distance away by the receiver. In the measurements the distance between the two transducers is varied giving rise to changes in the signal arrival time of the Rayleigh wave pulse. Figure 1 is a plot showing sample data on rocks 14310, 15555, and synthetic analogue of rock 10017. The slope of the lines through the data points give the absolute group velocities independent of any inaccuracies in the absolute position or signal arrival time determinations. Spectrum analysis of the received signal gave a maximum at a frequency of about 2 MHz in the fine grained rocks. For rock 15555 the major frequency component dropped to about 700 kHz suggesting the presence of extensive scattering by the coarse grains in this rock.

B. Discussion:

The lunar samples, with the exception of 14321, are igneous rocks of competent, cyrstalline composition. Lunar rocks 14310 and 12063 have velocities which are lower by a factor of as much as three from those typically measured in terrestrial basalts. Our measurement on a sample of basaltic flow from northern California gave 2.97 - 3.15 km/sec for comparison. A similar difference was observed with bulk waves (Wang et al., 1971; Warren et al., 1971; and Kanamori et al., 1971) and has been explained as being due to the presence in lunar rocks of unfilled micro-fractures. Using the density and elastic constants for rock 12063 from measurements of Warren et al. (1971) and assuming that the phase and group velocity vectors are co-linear (Daniel and De Klerk, 1971), we calculated the Rayleigh wave velocity from the expressions given by Mason (1958). The calculated velocity values range from 1.27 to 1.64 km/sec and thus tend to be higher than those measured by us directly, although the difference is small compared to the total range of bulk velocities reported thus far.

In contrast, petrological studies of rock 14321 by Duncan et al. (1972), Warner (1972), Swann et al. (1971) and the LSPET (1971) indicate that rock 14321 has had a complex and multistage formational history, and is part of a group of moderately thermally recrystallized polymict breccia. Microscopic examination of our sample 14321.211 suggests that it is a micro breccia of low coherence. Because of the sample friability, measurements could not be made in the normal manner but estimates of the velocity were obtained by the time of flight method giving the value of

0.9 km/sec. This value is slightly higher than but in approximate agreement with that calculated for another micro breccia, rock 10046, from bulk wave data of Anderson et al. (1970).

(a) Rock 12063: Our previous measurements (Tittmann and Housley, 1971) of the Rayleigh wave group velocity on lunar rock 12038 and bulk wave data reported by Wang et al. (1971) and Warren et al. (1971) suggest changes of velocity with propagation direction. This was checked by measuring the relative changes in signal arrival time systematically as a function of angle at fixed transducer separation on one surface of a cube about 2 cm on an edge cut from rock 12063. As the angle θ between the propagation direction and one sample edge taken as reference was increased, a systematic rise in velocity was observed for low angles followed by a decrease and leveling out of the velocity at higher angles. This result is shown in the solid line in Fig. 2. Polished section optical microscopic examination of rock 12063 showed that microfractures, vesicles and ilmenite blades tend to be preferentially elongated in the direction $10 \leqslant \theta \leqslant 25°$, which gave higher velocity values. The total change in velocity amounted to 9%. Measurements of the linear compressibility of Apollo 11 samples by Anderson et al. (1970) showed anisotropy at low pressure which they also suggested arise from a preferential orientation of microfractures. We mapped the surface of 12063 by the scanning electron microscope at magnifications from about 50 to 500, and found that on a statistical basis the microfractures showed a preferred orientation in the direction in which the velocity was highest. Figures 3a, 3b and 3c show sample micrographs of a small portion of the surface. The width of the microfractures observed ranged from 0.001 to 0.3 mm with most of them about 0.01 mm in width. A rough estimate of the surface area of microfractures ranged from 5 to 15% of the total surface area. Therefore it would appear that one contribution to the velocity anisotropy may be a result of the material being more compliant for stresses perpendicular to the fractures. Thus, if there is an anisotropy in the distribution of fracture directions, one may expect an anisotropy in the compliance and therefore in the velocity of sound. In an effort to shed more light on the effect of microfractures on the velocity, the sample was saturated with a low surface-tension fluid, reagent grade ethanol, and the velocity monitored as the alcohol was allowed to leave the sample by evaporation and then by evacuation to 10^{-8} mm of Hg. As shown in Fig. 4a, the velocity decreased from 1.61 to 1.26 km/sec with a net change of 25%. This result demonstrates that the presence of microfractures and their degree of filling can have a pronounced effect on the velocity of Rayleigh waves.

Since our sample 12063 was in the form of a cube, three of whose faces were smooth enough for Rayleigh wave measurements, the measurements described above were extended to the other faces to test the uniformity of the sample through its thickness. Table II present velocity values obtained along various directions and faces on the cube (See Fig. 2 for reference.)

Table II

Direction	Face	Velocity (km/sec)	Comments
x	(1)	1.23	
y	(1)	1.15	path contains pronounced fracture (~ 0.3 mm wide at surface)
z	(3)	0.91	
x'	(2)	1.00	
y'	(2)	1.23	

Also measurements were performed on each of two orthogonal cube faces with the two transducers moving parallel at a constant separation of about 9.5 mm across the entire face. Identical values of arrival time would have been expected for a uniform sample. In fact, variations of up to about 3% were observed for about 1 cm travel. The dashed line in Fig. 2 shows the variation of velocity with angle on the face opposite to that corresponding to the solid line. Although the widths and angular positions of the velocity peaks are not identical their resemblance suggests that the origin of the anisotropy in the surface velocity values arises at least in part from inhomogeneity trends which extend throughout the entire sample. Any interpretation linking these observations with large scale trends must await the study of many samples, so that effects caused by local inhomogeneities can be eliminated.

(b) Synthetic Analogue of Lunar Rock 10017: In an effort to gain more insight into the source of microfractures and their influence on the Rayleigh wave velocity, we studied a synthetic analogue of rock 10017, a lunar basalt whose Rayleigh wave velocity $v_R \approx 0.95 - 0.97$ km/sec we calculated from bulk wave data (Anderson et al., 1970). On the scanning electron microscope the synthetic rock showed considerably fewer microfractures (Fig. 3c) than either the lunar rock 10017 itself (Anderson <u>et al</u>., 1970). or our lunar rock 12063 (Fig. 3a, 3b and 3c). The Rayleigh wave velocity values measured on the synthetic rock were found to be correspondingly high, i.e. v_R = 2.21 - 2.26 km/sec, a factor of more than two higher than those calculated from bulk wave velocities. Therefore it seems probable that microfractures other than those introduced during the process of cooling from the melt contribute significantly to the reduced velocities of lunar samples. Next the synthetic rock was subjected to thermal cycling in order to determine whether the diurnal temperature variation on the lunar surface has any significant effect on the number of microfractures. The sample was cycled 2600 times between 300°C and -200°C with the temperature decrease in the cycle being accomplished by a rapid quench. However, petrographic examination showed no detectable change in the distribution, density, or size of microfractures. These experiments suggest that the diurnal cycling alone cannot account for the presence of microfractures, but rather the more intense thermal and mechanical shocks associated with meteoric impact, as has been suggested by Baldridge and Simmons (1971) or by high temperature subsolidus thermal cycling (Wang <u>et al</u>., 1972). From the above studies it seems probable that the velocities observed in the sysnthetic rocks may be representative of velocities in lunar basalts which have not been fractured at or near the lunar surface.

(c) Lunar Rock 15555: Velocity data collected on 15555 were obtained on many locations on different sample faces, and fell into the range 0.28 - 0.34 km/sec (Tittmann et al., 1972). These values are three to four times lower than those observed on lunar igneous rocks measured previously, and less than half those obtained on lunar breccias, as shown in Table I. Time of flight measurements of the bulk longitudinal wave velocity also gave low values, i.e. $v_P \approx 0.9 - 1.2$ km/sec. Although these values are approximate they appear to be somewhat higher than what would be expected from the observed Rayleigh wave velocity for an assumed density of $\rho = 3.1$ gm/cm^3 and Poisson's ratio of $\sigma \approx 0.23$. Microscopic examination showed that 15555 is a coarse grained olivine basalt with irregularly distributed vugs. Although the rock is highly fractured (see Fig. 3d and 3e) it shows little evidence of severe shock metamorphism. Care was taken to make the Rayleigh wave velocity measurements on the more massive portions of the rock where the vugs were sparsely distributed and did not exceed about 0.1 mm in size. The sample appears coherent and competent in normal laboratory handling and it is believed that our values probably represent intrinsic properties.

The existence of a very low elastic wave velocity in this generally competent, igneous rock indicates that the existence of a thick, low velocity zone near the lunar surface does not necessarily require postulating the existence of a thick layer of fines on the moon's surface.

Field observations (Swann et al., 1971) have concluded that the regolith in Station 9a at the Hadley Rille rim at which the sample was collected is very thin or absent and that most of the samples collected in this area are probably representative of the local bedrock exposed at the rille rim. From the discussion by Swann et al. (1971) we are not sure of the exact source of rock 15555. However, this rock is classified (LSPET, 1972) as typical of the porphyritic olivine basalts and similar in this respect to 15535 which is judged most certainly representative of the bedrock. Thus the assumption that 15555 may have been derived from the upper part of volcanic bedrocks exposed in the vicinity of the Hadley Rille seems justified. If this conclusion is borne out by further studies, the unusually low velocities measured on this igneous rock should be taken into consideration in the interpretation of the low seismic velocities observed in the upper layer of the lunar surface.

III. Q-Factor Measurements

A. Introduction:

The impulse technique was also used to measure relative changes in values for the Rayleigh wave attenuation by recording the change in the amplitude of the received signal as a function of environmental changes. In previous experiments (Tittmann and Housley, 1971), substantial relative changes in Rayleigh wave amplitude had been observed in rock 12038 when the absolute air pressure was changed from 1 atmosphere to 6×10^{-7} mm of Hg. The amplitude increased by a total of 25% as the pressure was reduced with most of the change occurring between

between one atmosphere and 1 mm of Hg. In tests where the sample was previously outgassed, then pressurized with dry nitrogen gas, this change between atmospheric pressure and 1 mm of Hg was absent. This result is similar to the results obtained in bulk wave experiments by Warren et al. (1971). It is well known from adsorption studies that an estimated 10 to 20 monolayers of H_2O can be adsorbed onto glass and silicate surfaces when exposed to the atmosphere. On the basis of these results and other considerations, it is believed that the trapping of water molecules in the microfractures is an important factor in decreasing the Q when the lunar return samples are allowed to come in contact with air. The source for the attenuation is believed to arise from water molecules collected in the regions of the fracture tips. During the passage of a sound wave pulse, the relative displacements of opposing fracture faces can be expected to effectively shorten the crack depth. This motion of the small amount of liquid trapped in the fracture probably gives rise to losses due to the viscosity of the liquid. When our sample was saturated with ethanol and then evacuated to 7×10^{-8} mm of Hg, the relative amplitude of the Rayleigh waves increased by a factor of 3.75 as shown in Fig. 4b. This rather substantial change dramatizes the effect of filling of the microfractures on the relative Q of the sample. These more qualitative studies of relative changes in Q-factor were followed by quantitative measurements of the absolute Q-factor by the vibrating bar technique, as described below.

B. Summary of Experimental Results:

Absolute Q measurements were performed by the vibrating bar technique on a 2 cm long bar cut from rock 14310, a recrystallized basalt (Ridley et al., 1972). The results are presented in Table III.

Table III

Environmental Description	Absolute Q Factor
Water Vapor	10
Laboratory Air (humid-dry day)	50 - 90
5×10^{-8} mm Hg	150
-180°C and 5×10^{-8} mm Hg	800 (highest achieved)
Terrestrial Rock in lab air	65

In the vibrating bar technique, the sample (typically 2 cm long, 2 - 3 mm thick) is held in the center by two needle point set screws and is vibrated in the longitudinal mode at its resonance fundamental by a magnetic drive. The transducers are small soft-iron buttons bonded on each end, one as transmitter the other as receiver. Because of the small separation between the coils of the magnetic drives, extensive shielding with μ-metal is necessary to reduce background due to direct coupling. The sample mount and magnetic drivers are mounted on a platform in a bell jar and can be cooled or heated as necessary, the temperature being monitored with a thermocouple in contact with one of the set screws holding the sample. In Fig. 5 is shown a sample plot of data of the frequency response with a Q estimated from the half width of the resonance curve of $Q \approx 70$ at STP and $Q \approx 700$ at $T \approx -180°C$ and $P = 6 \times 10^{-8}$ mm of Hg.

C. Discussion:

The vibrating bar technique was used to shed more light on the influence of water vapor on absolute Q of lunar rock (Pandit and Tozer, 1970). Sample 14310 was exposed to hot water vapors as the Q was being monitored and found to diminish drastically. Exposure to hot water vapors for about 30 seconds lowered the Q from a $Q \approx 90$ to about $Q \approx 10$. Longer exposures rendered the Q so low it was unmeasurable. Repeated experiments confirmed the conclusion that the lunar rocks we studied are quite permeable, adsorb H_2O at a rapid rate, and as a result change their Q drastically. Figure 6 shows the effect of exposure to water vapor on the frequency response curve of 14310.

In a similar manner the vibrating bar technique was used to monitor the absolute Q as the sample was exposed to a hard vacuum of 5×10^{-8} mm of Hg. At room temperature the Q was found to increase to values in the range $Q \approx 130 - 150$. Adsorption studies of H_2O on silicates suggest that this increase in Q is probably attributable to the removal of adsorbed water molecules from the microfractures.

The above experiment was extended by lowering the temperature of the sample while in the hard vacuum. This was accomplished by circulating cold N_2 gas through a Cu tube coiled around and soldered onto the sample holder platform. In this way sample temperatures down to -185°C could be obtained. The Q was found to increase with decreasing temperature with the highest values $Q \approx 400 - 800$ found near $T \approx -180$°C at a vacuum of 6×10^{-8} mm of Hg. The highest Q value achieved appears to depend somewhat on such factors as the lowest equilibrium temperature achieved concomitant with the hardness of the vacuum, the quality of the transducer bond, and the nearness of the sample holding set screws to the ideal nodal point. The sample itself was not ideal in shape having a rather nonuniform cross section. Therefore the higher Q values are probably closer to the real Q and it is felt that optimization of all the parameters could achieve even higher values. The detailed mechanism for the increase in Q with decrease in temperature is not understood at this time. However, since the sample is allowed to be outgassed at 1×10^{-7} mm of Hg for a considerable amount of time the mechanism probably has little to do with the freezing of adsorbed water molecules. The well known mechanism for damping by Coulomb friction between adjacent grains is not likely to give rise to any strong temperature dependent effect. A thermally activated relaxation mechanism seems to be the most probable source of damping. If so, detailed studies of the temperature and frequency dependence should reveal the source and nature of this mechanism.

IV. Summary Discussion

The observations described above leave little doubt that the presence of microfractures influence both the velocity and Q-factor values of lunar rocks. Velocity data but especially Q data appear to be influenced by the high degree of contamination by terrestrial atmosphere, emphasized because of the permeability of the lunar rocks. Water vapor especially appears to affect Q values drastically. The high Q values observed at temperatures near $T \approx -180^{\circ}C$ suggest the action of some unknown mechanism for the damping observed in measurements at standard temperature and pressure in earth's environment which are apparently not present on the moon. Correlations between data of seismic and laboratory experiments on terrestrial rocks suggest strongly that Q-factors are independent of frequency up to the regime of Rayleigh scattering. It is with this basic premise not yet proven for lunar rocks that the present Q measurements at frequencies below 100 kHz were made and interpreted. Our highest observed Q value of $Q \approx 800$ still does not match those deduced from the seismic experiments but does approach the low end of the range of seismic Q.

With Rayleigh velocity data obtained on real lunar rocks and synthetic analogues we now have a broad range of velocity data available. These velocities cover about one order of magnitude from $v_R \approx 0.3$ km/sec to $v_R \approx 2.2$ km/sec and appear to represent the entire range from highly fractured to essentially non-fractured rocks. These velocities have all been obtained at zero confining pressure and are therefore representative of the more solid material in the upper few kilometers of the lunar surface. In view of this spread in velocities it is perhaps not surprising that seismic experiments executed in this layer show a high degree of scattering in the data.

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Figure Captions

Fig. 1 Sample data of change in signal arrival time as a function of the transducer separation for rocks 14310, 15555, and a synthetic analogue of lunar rock 10017. The data were obtained by the impulse technique (Tittmann, 1971). The reciprocal of the slope gives the Rayleigh wave group velocity.

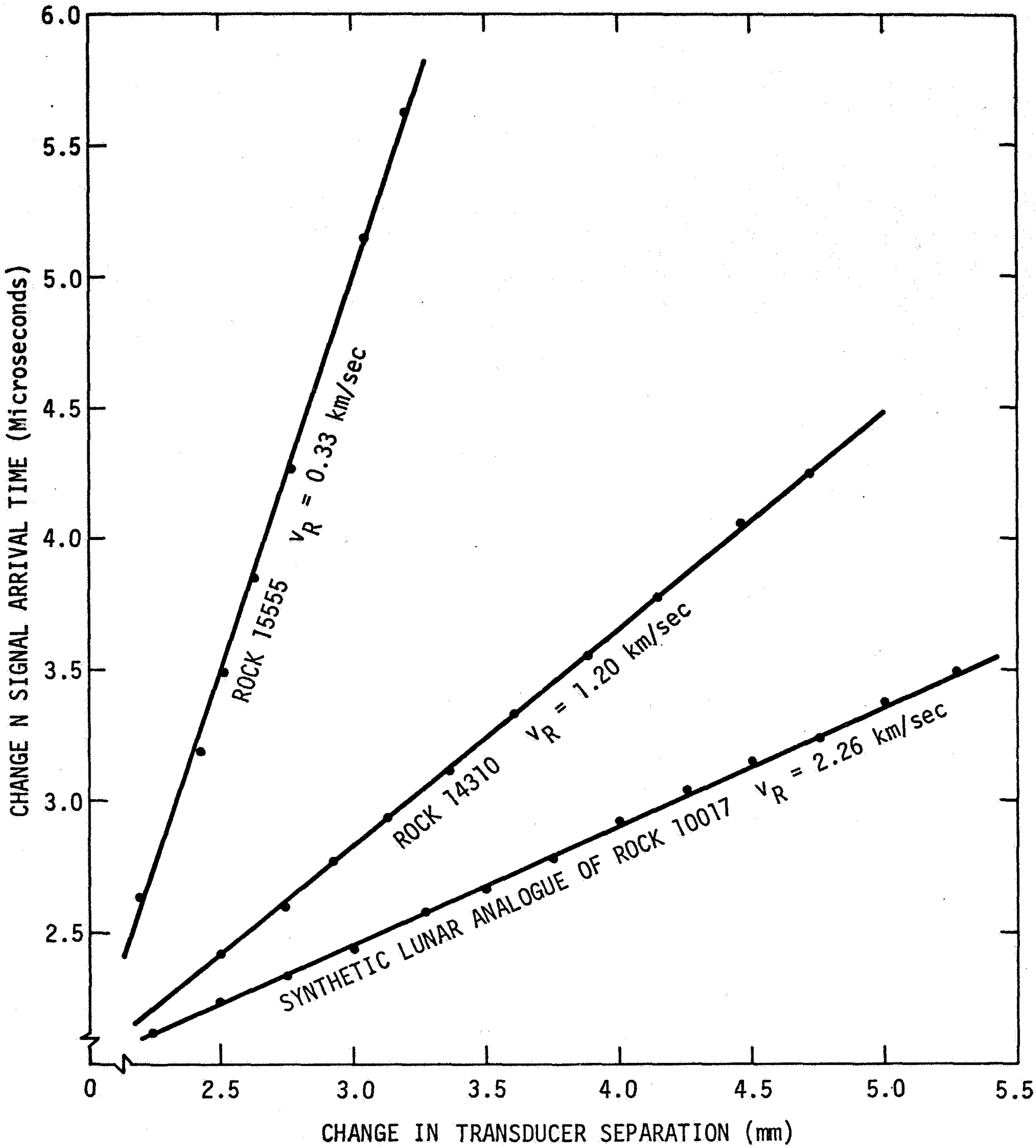
Fig. 2 Plot of Rayleigh wave velocity v_R as a function of angle θ between the direction of sound propagation and an edge of the sample chosen as arbitrary reference direction. The data were obtained for two opposite faces (solid line - face 1; dashed line - face 2) of rock 12063.96 (a cube of about 2 cm on edge) for several different separations d between transmitter T and receiver R.

Fig. 3 Scanning electron beam micrographs of rock surfaces exhibiting microfractures. (a) and (b) face 1 of rock 12063.96 (c) same as in (a) but enlarged 10 times. (d) synthetic rock lunar analogue 10017. (e) and (f) rock 15555.

Fig. 4 Rayleigh wave velocity and relative amplitude as a function of ambient gas pressure for rock 12063.96 (in the direction $\theta = 10^\circ$ on face 1) starting with the sample fully saturated with ethanol at atmospheric pressure and ending at about 5×10^{-8} mm of Hg.

Fig. 5 Data plot of amplitude of vibration of a bar of rock 14310 as a function of frequency near resonance at STP. The bar is driven in the free-free mode of compressional waves.

Fig. 6 Curves of amplitude of vibration as a function of frequency for rock 14310 in a series of oscilloscope traces showing from left to right how the Q diminishes the longer the bar is exposed to hot water vapors.



6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
CHANGE N SIGNAL ARRIVAL TIME (Microseconds)
0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
CHANGE IN TRANSDUCER SEPARATION (mm)
ROCK 15555 v_R = 0.33 km/sec
ROCK 14310 v_R = 1.20 km/sec
SYNTHETIC LUNAR ANALOGUE OF ROCK 10017 v_R = 2.26 km/sec

Figure 1

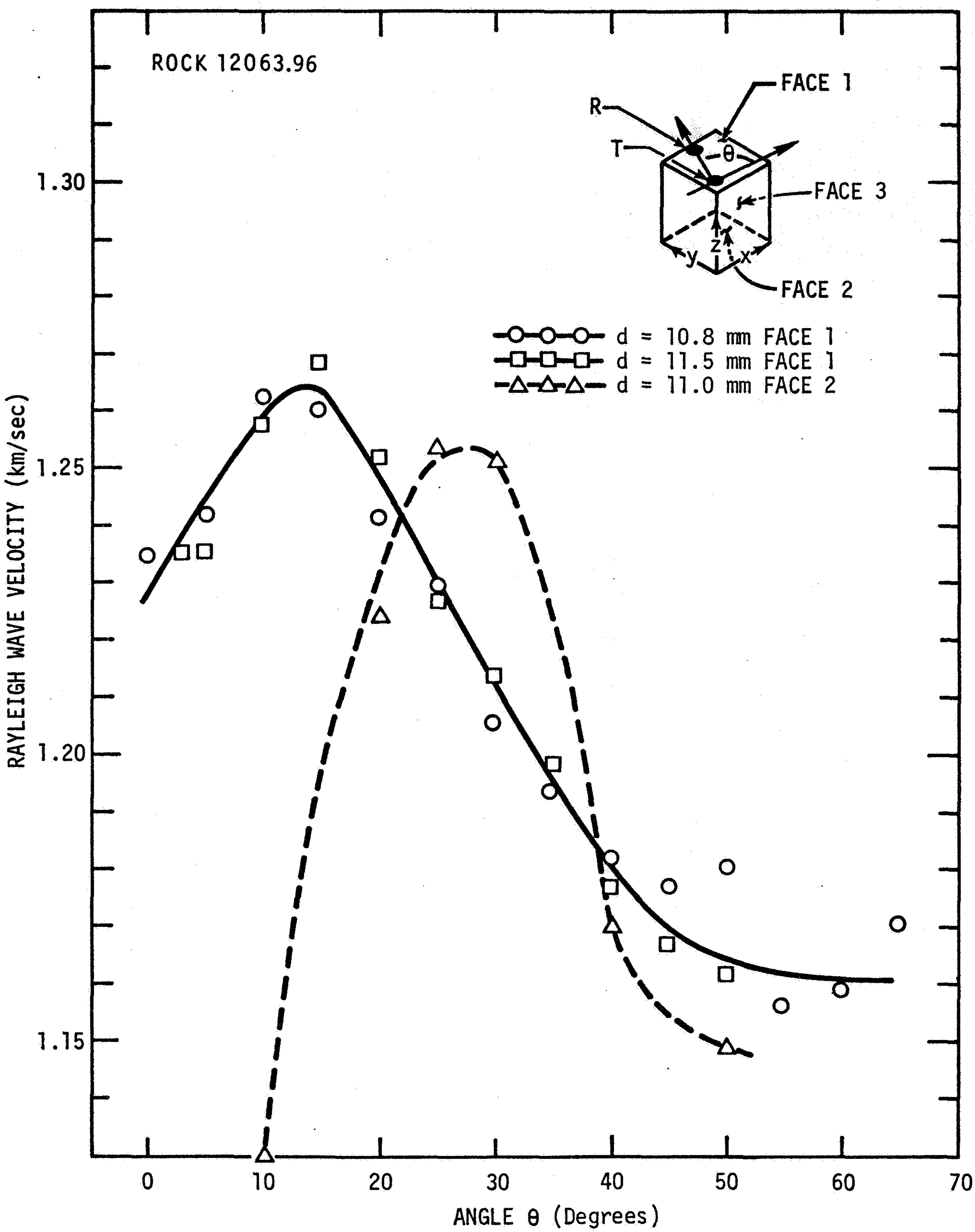

ROCK 12063.96
FACE 1
R
T
θ
FACE 3
z
y
x
FACE 2
d = 10.8 mm FACE 1
d = 11.5 mm FACE 1
d = 11.0 mm FACE 2
RAYLEIGH WAVE VELOCITY (km/sec)
1.30
1.25
1.20
1.15
0
10
20
30
40
50
60
70
ANGLE θ (Degrees)

Figure 2

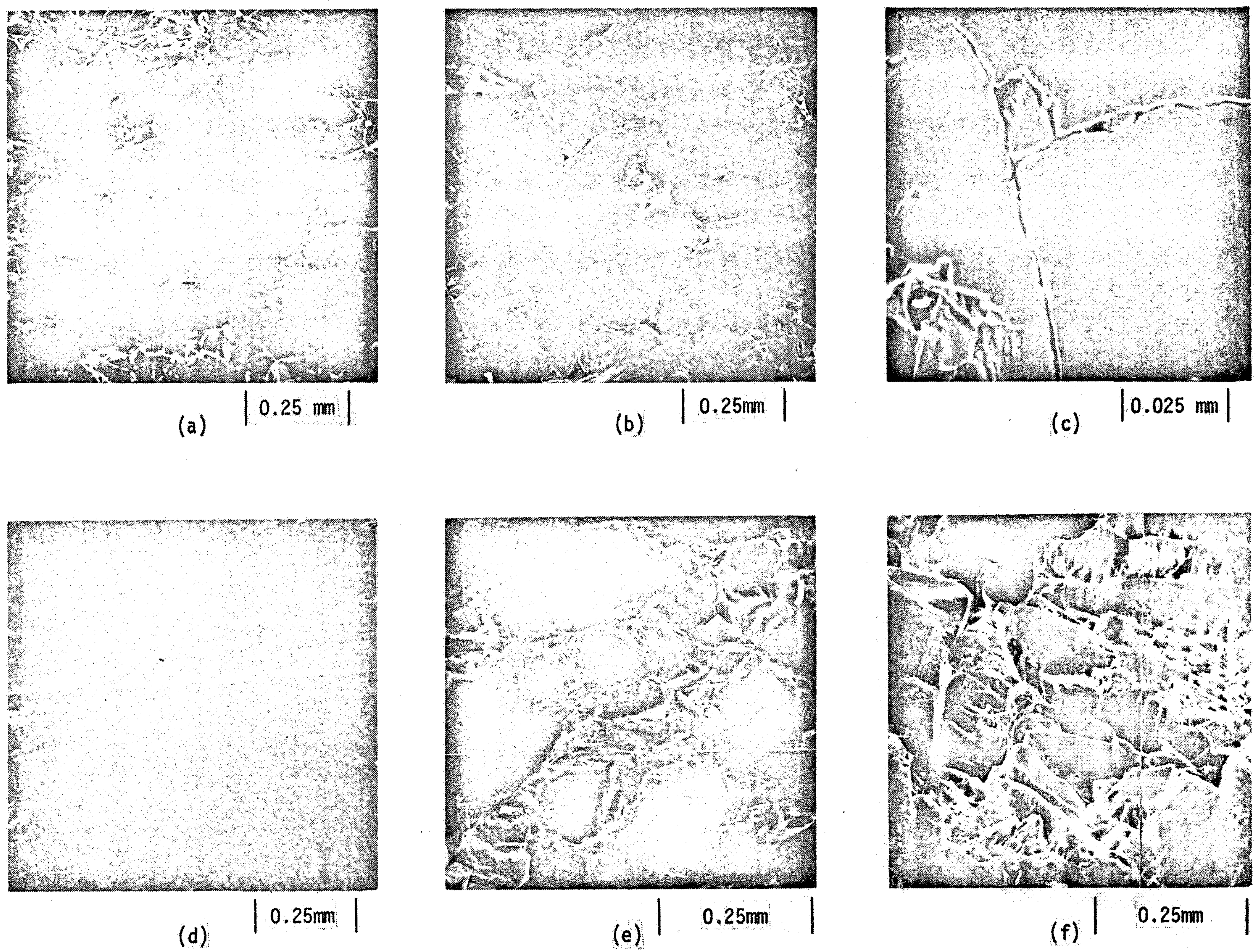


Figure 3

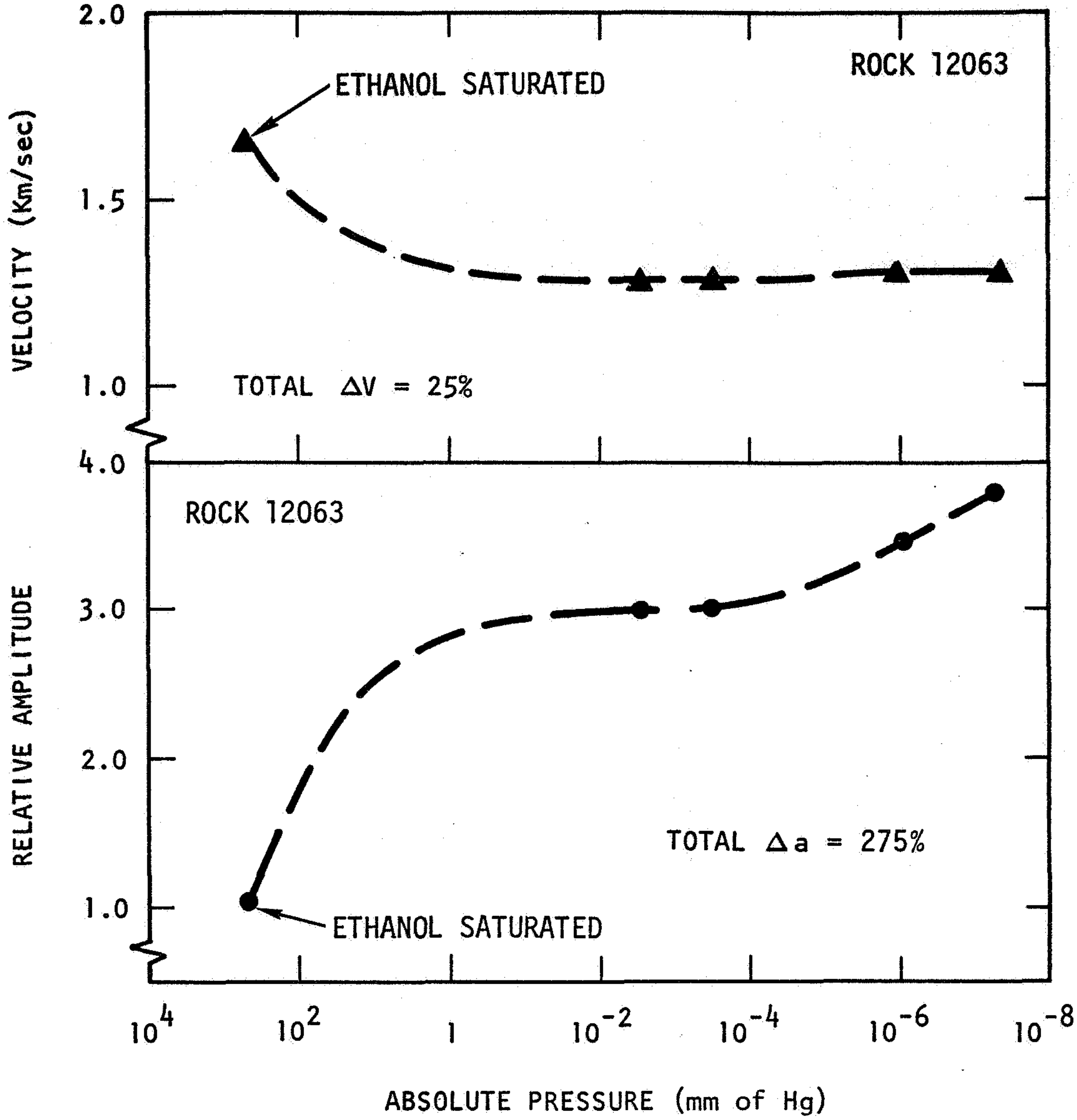

ROCK 12063
ETHANOL SATURATED
VELOCITY (Km/sec)
2.0
1.5
1.0
TOTAL ΔV = 25%
4.0
ROCK 12063
RELATIVE AMPLITUDE
3.0
2.0
1.0
TOTAL Δa = 275%
ETHANOL SATURATED
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
ABSOLUTE PRESSURE (mm of Hg)

Figure 4

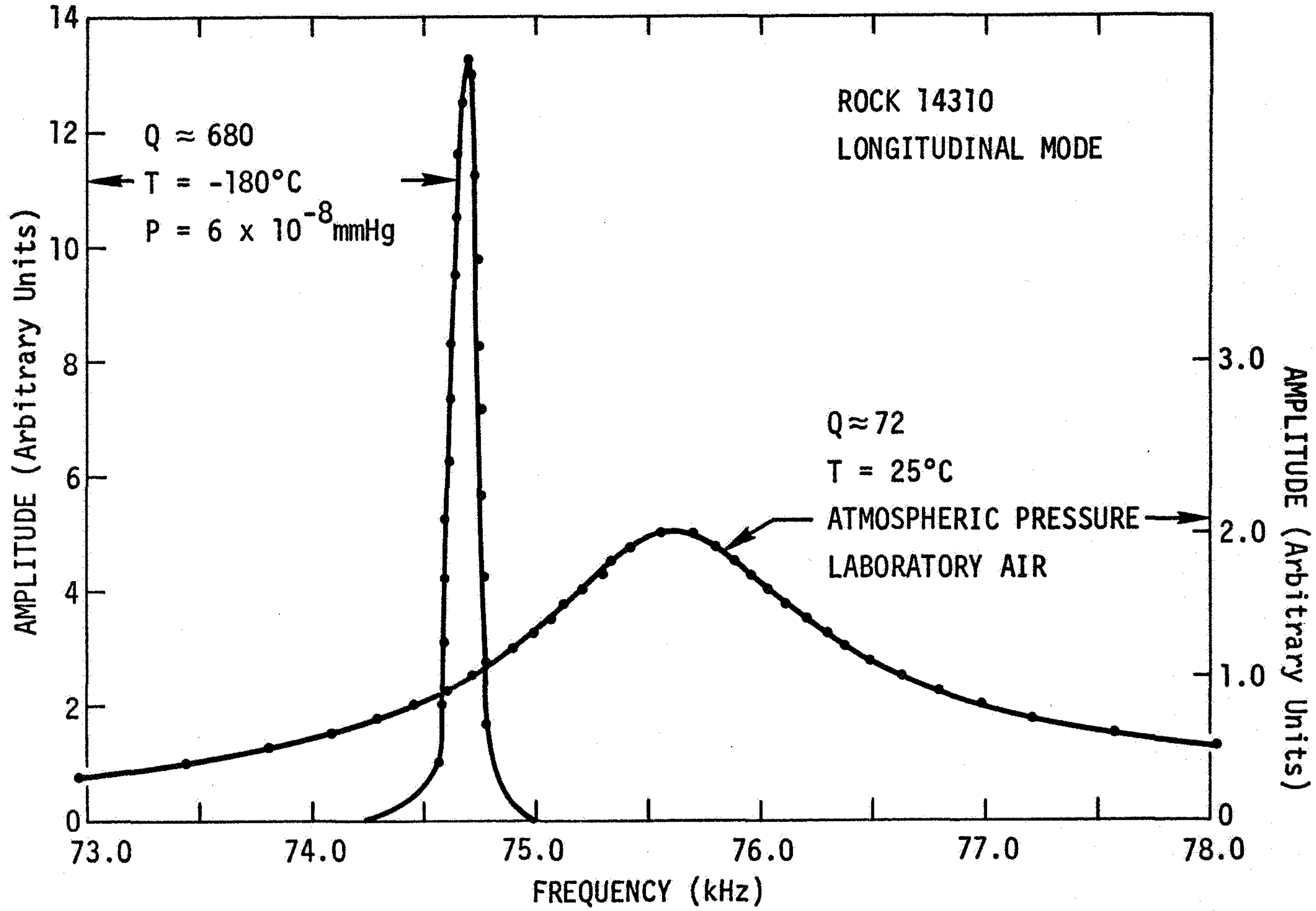
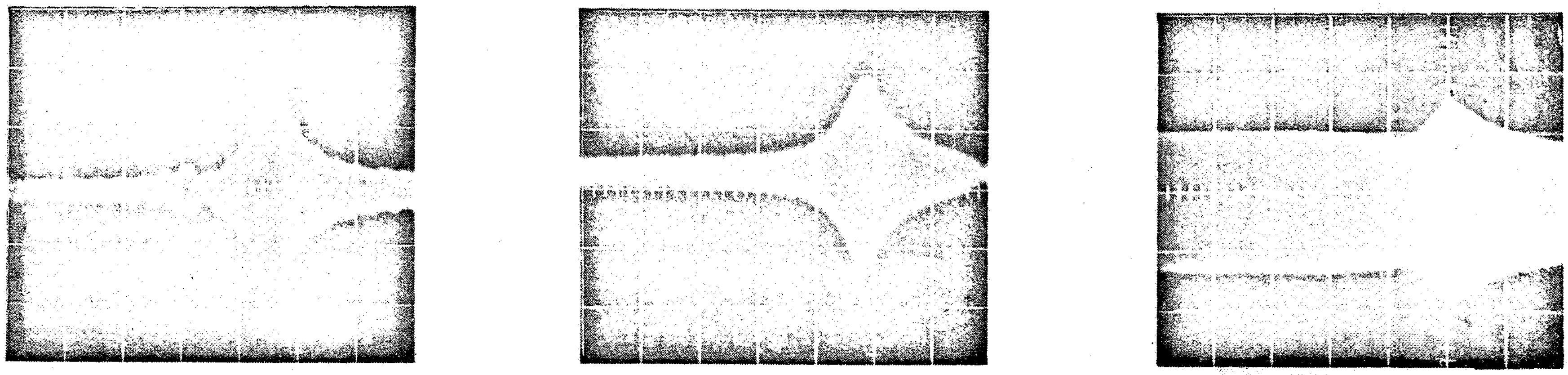

ROCK 14310
LONGITUDINAL MODE
Q ≈ 680
T = -180°C
P = 6 x 10-8 mmHg
Q≈72
T = 25°C
ATMOSPHERIC PRESSURE
LABORATORY AIR
AMPLITUDE (Arbitrary Units)
FREQUENCY (kHz)
AMPLITUDE (Arbitrary Units)
0
2
4
6
8
10
12
14
73.0
74.0
75.0
76.0
77.0
78.0
0
1.0
2.0
3.0

Figure 5



(a) Q = 70 (b) Q ≈ 35 (c) Q ≈ 10

Figure 6